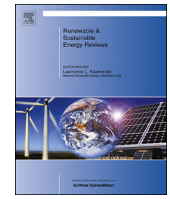
Renewable and Sustainable Energy Reviews 27 (2013) 94–103

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations

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A R T I C L E I N F O

Article history:
Received 6 March 2013
Received in revised form
22 May 2013
Accepted 28 June 2013
Available online 20 July 2013

Keywords:
HVAC scheduling
Energy efficient operation
Energy conservation measure
Building's energy consumption

A B S T R A C T

This paper provides a detailed review on heating, ventilation and air conditioning (HVAC) scheduling techniques for buildings towards energy-efficient and cost-effective operations. The scheduling techniques can be divided into 3 main classes, which are the basic techniques, conventional techniques and advanced techniques. The basic scheduling technique involves only the manipulation of the 'ON' and 'OFF' states of the HVAC system whereas the conventional scheduling technique uses pre-cooling or pre-heating techniques to reduce the peak demand with the use of several setpoint temperatures. The characteristics, as well as the energy and cost saving potentials for each strategy are presented. The advanced scheduling technique, which is the improved version of the basic and the conventional scheduling techniques is found to have the highest energy and cost saving potential. The limitations of the scheduling techniques have also been identified and possible solutions to overcome these limitations and improve the scheduling performance further have also been briefly stated.

Contents

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http://dx.doi.org/10.1016/j.rser.2013.06.041

1. Introduction

Energy conservation measure (ECM) is a practice conducted in a building for the purpose of reducing energy consumption caused by the electrical systems such as lighting, heating, ventilation and air conditioning systems. ECM is also a way to determine several potential alternatives for reducing energy consumption and deciding which alternatives must be implemented. Energy conservation must be done without sacrificing the comfort of the occupants in the building [1]. ECMs have been implemented widely in buildings for energy saving initiatives in the recent years [1–25]. ECMs can be categorized based on the amount of financial investment involved in its implementations: zero investment, minor investment and major investment [1,3,6]. There are two basic ways of conserving energy using the ECM approach. The first method involves physical alterations or additions to the existing system in the building such as complete system replacements or installation of sensors for lighting system, and the second method requires only changes to the operation of the system such as scheduled lightings or air conditioning operating times.

Since the use of heating, ventilation and air conditioning (HVAC) system accounts for one of the highest percentage of energy use in a building, ECM for HVAC systems is a popular research topic and has attracted many building owners in their effort to minimize the buildings' energy consumption [1–6,10–12,17–22,24,25]. ECMs on HVAC systems also result in the highest energy saving potential compared to its application on the other electrical systems in a building [1,5,6,20–22]. HVAC's ECMs can either be a zero investment ECM by, for instance, changing the thermostat temperature setting; or a major investment ECM by, for example, replacing the existing HVAC system with a more energy-efficient HVAC system [1].

In the recent years, ECMs focusing on HVAC operation scheduling becomes popular because of the considerably high energy saving potential that it can provide. Some of the operations scheduling techniques are discussed in [1–4,6,8,21,25]. In these proposed techniques, the scheduling processes are quite simple and are mainly based on the occupancy of the building. For example, if the building is occupied, the setpoint temperature of the air-conditioning system will be reduced, and during unoccupied time, the setpoint will be changed to higher temperatures. These setpoint temperatures must also be within the thermal comfort range so as not to sacrifice the comfort of the building's occupants in the effort to reduce the energy consumption. Also, in most of the previously used HVAC scheduling approaches, the HVAC is operated for 24 h daily with the night setback technique, which is an approach to reduce energy usage by increasing the setpoint temperature during unoccupied hours. This, in general, does not maximize the energy saving potential of the air conditioning system. Therefore, a great numbers of scheduling techniques have been proposed and developed for the purpose of maximizing the energy saving potential while preserving the comfort of the occupants in the building or the space.

In this paper, several methods of scheduling the HVAC operation are discussed. The methods are divided into several classes and discussed in Section 2 of this paper with the illustration of the temperature setpoint throughout the day according to the related sources. Firstly, the simple methods of HVAC scheduling are explained. This is followed by the discussion on the conventional scheduling techniques that primarily aim to reduce the peak energy demand. Another class of HVAC scheduling methods discussed in Section 2 is the advanced scheduling method. The discussions mainly focus on how each scheduling technique works, what makes it different from other scheduling techniques, the energy saving potential as well as its limitations and possible modifications that can be made. Section 3 will discuss about the use of comfort index, Predicted Mean Vote (PMV) and its relationship with outdoor temperature. The paper ends with a summary and conclusions that can be drawn from all the scheduling techniques explained that also includes some recommendations for developing new HVAC scheduling techniques.

2. Types of HVAC scheduling

In this paper, the HVAC scheduling techniques are divided into three classes; basic techniques, conventional techniques and advanced techniques. The basic scheduling technique involves only the manipulation of the 'ON' and 'OFF' states of the HVAC system. Meanwhile, in the conventional scheduling technique, the setpoint temperatures of the HVAC system are manipulated and this is the most popular technique implemented in buildings. Advance scheduling is the improved technique that is based on the basic and the conventional scheduling techniques or the combinations of both.

2.1. Basic HVAC scheduling techniques

The basic HVAC scheduling technique has been discussed in great details in [26] where four simple techniques of scheduling the operation of a HVAC system been proposed. The four scheduling techniques discussed are: interruption, early switch-off, demand reduction and alternate switch-on/off. It has been concluded that each of the techniques has the potential to reduce the amount of electrical energy consumed by the HVAC. The effects of combining some of the four techniques have also been discussed. In the building in which the basic techniques were tested in [26], the HVAC heating setpoint temperature was fixed at 22 °C throughout the operation period from 0900 to 2100 h, which is the normal occupied hours of the building.

2.1.1. Interruption

For a heating system, the first strategy of the basic HVAC scheduling technique is done by interrupting the HVAC operation by switching it off for several hours during the occupied period, as shown in Fig. 1. The HVAC is switched on from 0900 until 2100 h, but during the warmest period of the day, the HVAC is turned off for several hours (e.g. 1200 until 1500 h), and then the HVAC will be operating again until it is switched off at 2100 h.

Meanwhile, for the air-conditioning system, interruption can also be done during the same hours considering that there will be less people inside the building as most are out for lunch. However, the interruption should only be done for only one or two hours to avoid the space from becoming too warm.

2.1.2. Early Switch Off (ESO)

The second strategy involves early switch-off of the HVAC system in order to reduce the energy consumption. For example, the HVAC starts to operate at the beginning of the office hours at 0900 but it is switched off two hours earlier before the building is normally empty as people start to leave the building. This approach requires accurate information on the occupants' time of occupation in the building to ensure that the early switch off technique does not cause much discomfort to them. Fig. 2 shows the states of the HVAC system for the early switch off approach.

2.1.3. Demand Reduction (DR)

As shown in Fig. 3, the third strategy is done by pre-heating the space during the off-peak period (from 2000 until 0800 h) several hours before the space is occupied, for example, from 0600 to 0700 h. This is done to take the advantage of the lower electrical pricing during the off-peak period and to reduce the HVAC demand

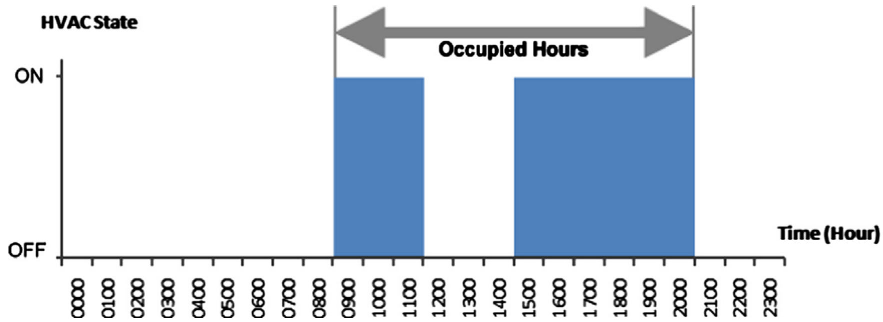

Fig. 1. Interruption technique in the HVAC operation from 1200 to 1500 h.

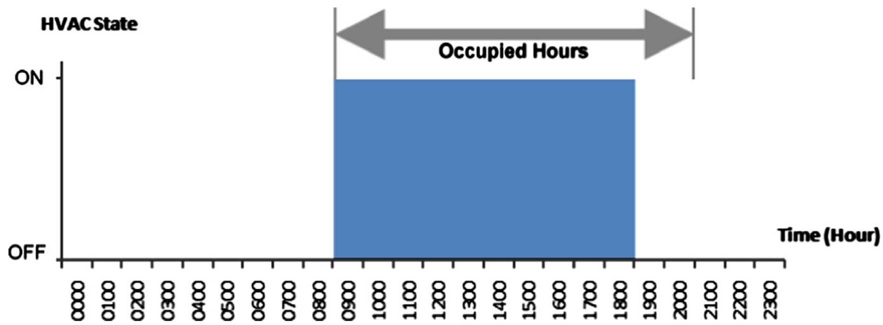

Fig. 2. Switching off HVAC 2 hours early.

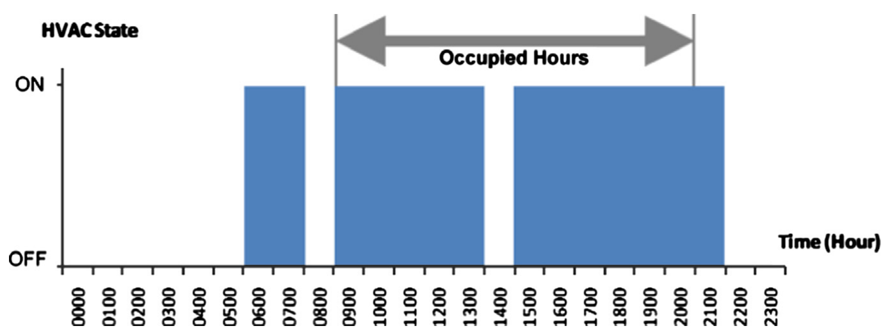

Fig. 3. Pre-heating in the demand reduction (DR) technique.

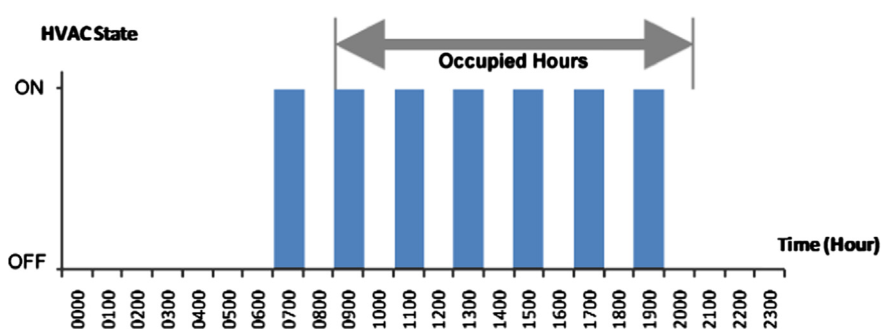

Fig. 4. Alternately switching on and off the HVAC for every one hour.

during the peak hours. By pre-heating the building during the off-peak hours, the demand during peak hours can be moved to the off-peak hours. After pre-heating during the off-peak hours, the HVAC will be switched off for a while (between 0700 to 0800 h) in order to reduce the energy usage during the peak hours. As shown in Fig. 3, the HVAC can also be turned off again at noon (1400 to 1500 h) during the lunch break. It is also important to note that the pre-heating duration must be shorter than the morning peak (e.g. 0900–1200 h).

2.1.4. Alternate Switch-On/Off (ASOO)

The fourth strategy in the basic HVAC scheduling approach is done by alternately switching on and off the HVAC system during the operational hours. The HVAC is repeatedly turned on and off, for example, every 30 min or one hour intervals, as shown in Fig. 4.

Table 1 shows both the energy saving (in terms of energy consumption reduction) and economic saving (in terms of electricity bills savings) of each of the basic HVAC scheduling techniques as well as the combinations of the techniques. The energy

saving and economic saving results are compared with the normal operation technique, which uses the setpoint temperature of 22 °C from 0800 to 2100 h. It has also been shown in [26] that by reducing the heating system setpoint temperature, cost and energy can be saved greatly. The effect is, of course, reversed if the setpoint is to be increased, as has been stated in [1] and [2].

Table 1 shows that the basic HVAC scheduling strategies and the combinations of the techniques may be able to save up to 20% energy and 21% cost for the HVAC system used for heating a building. Although slight modification of the techniques may be needed for the operation of the air-conditioning system, the basic principle and energy saving advantages remain similar.

Table 1
Energy and economic savings results for the basic HVAC scheduling techniques [26].

Technique	*Description*	*Energy saving (%)*	*Economic saving (%)*
Interruption	Switch-off *period:* 1200–1300 *h*	*2.93*	*5.05*
	Switch-off *period:* 1200–1500 *h*	*5.66*	*6.37*
ESO	Switch-off *time: 2000 h*	*4.48*	*5.45*
	Switch-off *time: 1900 h*	*11.19*	*8.78*
DR	Pre-heating *period:* 0700–0800 *h* Switch-off *period:* 0800–0900 *h*	*– 11.22*	*– 13.91*
	Pre-heating *period:* 0500–0800 *h* Switch-off *period:* 0800–0900 *h*	*– 31.59*	*– 1.18*
DR	Pre-heating *period:* 0600–0700 *h*	*2.74*	*8.36*
Interruption	Switch-off *period* (1st): 0800–0900 *h* Switch-off *period* (2nd): 1400–1500 *h*		
ASOO	*On/Off (1 h):* 0700–2100 *h*	*20.31*	*19.4*
ASOO	*On/Off (1/2 h):*1000–2100 *h*	*7.55*	*17.62*
DR	Pre-heating *period:* 0600–0800 *h* Switch-off *period:* 0800–0900 *h*		
DR	Pre-heating *period:* 0500–0800 *h*	*7.48*	*21.11*
Interruption	Switch-off *period:* 1200–1500 *h*		
ESO	Switch-off *time: 1900 h*		
	Pre-heating *period:* 0600–0800 *h* Switch-off *period:* 1300–1500 *h* Switch-off *time: 2000 h*	*18.82*	*19.25*

ESO: Early Switch Off, DR: Demand Reduction, ASOO: Alternate Switch On/Off.

Table 1 also shows that the alternate switch-on/off (ASOO) offers the greatest savings. However, this technique, which requires the HVAC system to be frequently switched on and off, may be quite impractical and can cause the lifetime of the system components to be significantly reduced [27]. Another concern relates to the control system of the heating or air-conditioning system itself where without proper control strategies, too frequent switchings may cause too much overshoots and oscillations, which may reduce the comfort, energy and economic saving potential [28]. It can also be noticed that combinations of the techniques do not necessarily result in better saving performances compared to the implementation of the technique on its own.

2.2. Conventional HVAC scheduling techniques

The conventional HVAC scheduling technique is the most popular techniques to improve electrical energy consumption implemented in buildings. Its main characteristics are that the HVAC system operates for 24 h a day, it manipulates the setpoint temperatures of the HVAC system and uses the 'night setback' approach to achieve its energy saving objectives. For an air conditioning system, the 'night setback' is a way to reduce energy usage by increasing the setpoint temperature during unoccupied period, whereas for a heating system, this setpoint temperature is set to be lower than in normal operations. A higher setpoint is used in the night setback of an air-conditioning system in order to compensate for the lower temperature at night so that the resulting temperature is the normal room temperature. There are three conventional ways for scheduling the HVAC operations for the cooling system, as discussed in [29–32]. They are the baseline, step-up and linear-up scheduling techniques. The baseline technique is the most used technique for the HVAC systems. The step-up and linear-up technique revolves around the pre-cooling of a space for the purpose of reducing the peak demand. The following sections discuss all the three conventional HVAC scheduling techniques in details.

2.2.1. Baseline

The baseline approach is the most used HVAC scheduling technique due to its simple operation. In this technique, as shown in Fig. 5, the setpoint temperature is set to be at the lower boundary of the thermal comfort zone during the occupied period. During the unoccupied duration, night setback operation is used, in which the temperature is set to be significantly higher compared to the occupied setpoint temperature for the purpose of reducing energy consumption [33].

2.2.2. Step-up

The second strategy adopts the step-up approach in its operation, where the setpoint temperature of 21 °C is used to pre-cool the room at the beginning of the occupied period (from 0700 to

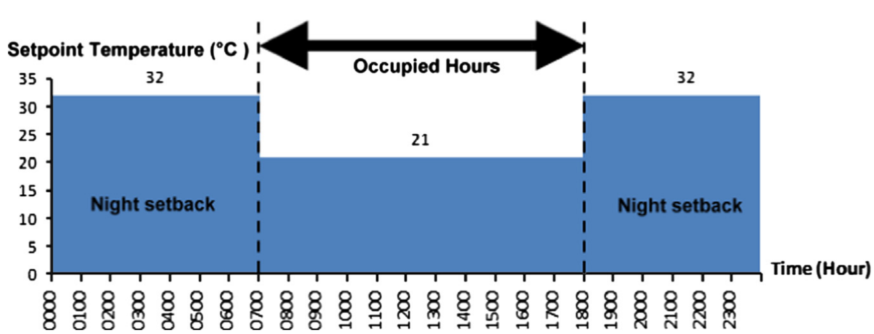

Fig. 5. Baseline technique for an air-conditioning system.

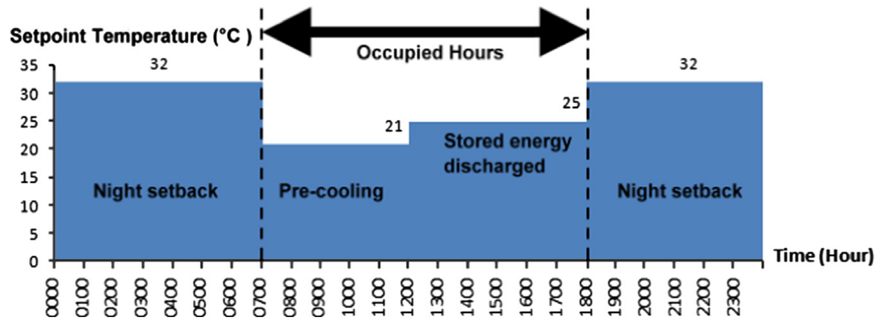

Fig. 6. Step-up technique.

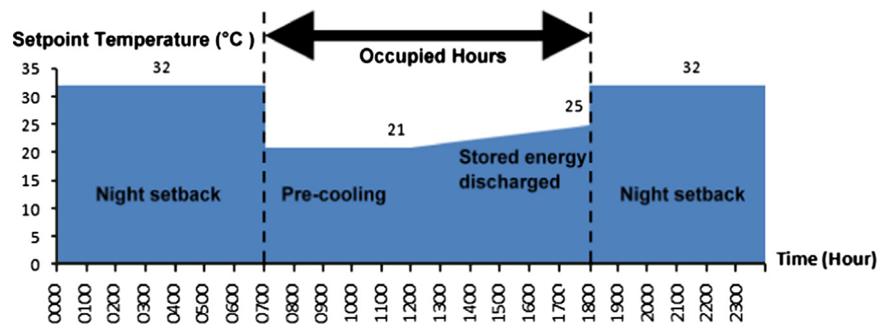

Fig. 7. Linear-up technique.

1200 h), as shown in Fig. 6. Then, after 1200 h, the setpoint temperature is raised to a higher value in order to discharge the cooled air stored during the morning operation, unlike the baseline technique that uses fixed low temperature throughout the occupied period. The similarity to the baseline technique is that, this technique also uses the night setback operation during unoccupied period.

2.2.3. *Linear-up*

The linear-up strategy is similar to the step-up technique but, instead of simply raising the temperature set point to constant value, it is raised in a linear pattern until it reaches the desired final setpoint temperature at the end of occupied period, as shown in Fig. 7. Night setback operation is also applied in this technique during unoccupied hours.

From [31] and [32], the daily energy saving potential for the step-up and linear-up conventional HVAC scheduling techniques compared to the baseline technique can be summarized in Table 2 below. It can be seen that by using the linear-up and step-up scheduling, peak demand can be reduced, hence reducing the overall daily energy consumption. Also, the step-up technique seemed to be more effective in reducing the peak demand.

For the air-conditioning or cooling system, lowering the setpoint temperature will generally increase the amount of electrical energy used. The pre-cooling process in all of the conventional scheduling techniques is done with low temperature setpoint during peak hours tariffs, which is significantly high compared to off-peak hours tariffs. Since the pre-cooling is done after a night setback, which uses setpoint temperature of 32 °C, the cooled air could not be stored instantly because it is used to reduce the 32 °C indoor temperature first. This will not maximize the pre-cooling effect and may cause discomfort to the occupants. This situation can be overcome by replacing the night setback operation with pre-cooling operation during unoccupied period or off-peak hours to take advantage of the low electrical tariff during the off-peak period. By doing so, the cool energy during pre-cooling will not be wasted to compensate with the high temperature since the

Table 2
Peak demand reduction performance of the linear-up and step-up scheduling techniques.

Technique	*Setpoint temperature during occupied periods*	*Peak demand reduction*
Baseline (reference)	*21 °C*	–
Linear-up	*21–25 °C*	*9.8%*
Step-up	*21–25 °C*	*21.37%*

outdoor temperature at night is low. Also, unlike the night setback process that is scheduled for the whole unoccupied period, the air-conditioner can be turned off for a certain amount of time before the pre-cooling operation during the off-peak hours to further reduce the energy consumption.

2.3. *Advanced scheduling techniques*

The advanced HVAC scheduling technique discussed in this review paper is defined as the improved version of the basic and conventional scheduling techniques. Four such techniques will be discussed in this section. They are the extended pre-cooling with zone temperature reset technique, the 5-period division scheduling, the aggressive duty cycling technique and the optimized demand limiting setpoint trajectories technique. The energy saving potential for these techniques are significantly higher than the basic and the conventional scheduling techniques.

2.3.1. *Extended pre-cooling with zone temperature reset*

Varying the temperature setpoints of a HVAC system in an optimal fashion and by shifting the cooling/heating loads from daytime to night time can reduce the energy peak demands as well as taking the advantage of the low off-peak electricity tariff [34]. It is based on these reasons that the extended pre-cooling technique is developed for the air-conditioning system. The normal pre-cooling is done by pre-cooling the zone from several hours before a building is occupied,

with the same temperature setpoint until the end of lunch hours, but the extended pre-cooling pre-cools the zone from midnight until very early morning, preserving the stored energy for several hours and then discharge it during the peak hours [35,36]. At the beginning of the extended pre-cooling process, the zone will be pre-cooled with a lower temperature compared to the normal pre-cool temperature for several hours. Then, the setpoint temperature will be increased by 1 or 2 °C for longer hours until the peak demand hours when the setpoint temperature will be increased even more. The illustration of the extended pre-cooling technique is shown in Fig. 8. Be it normal or extended, zone temperature reset is used to discharge the stored energy by setting the setpoint temperature to higher value after the pre-cooling period.

The reduction in the electrical energy consumed using this technique has not been stated in the work that is described in [36], but it has been mentioned that this approach has managed to shift 80–100% of the electrical load from the peak to the off-peak period. It is also important to note that the pre-cooling process should be done with a setpoint temperature that is lower than the thermal comfort temperature range. Although the air-conditioning system may use more energy during pre-cooling, this pre-cooling process in this technique is done during the off-peak hours, which has lower electricity tariff and therefore results in higher cost savings as well as significantly reduces the peak demand during the occupied hours [37].

2.3.2. 5-Period division scheduling

The 5-period division scheduling technique has been discussed in [38], where the day is divided into 5 sections, as shown in Fig. 9. The schedule is structured as in Table 3 and is based on Fig. 9. Thermal comfort region is the range of temperature, which does not cause any discomfort to the occupants of a space. The range varies according to the climate of a country. Upper comfort region is the upper half of the comfort temperature range. Lower comfort region is the lower half of the range. Meanwhile, the temperature outside the comfort region is either hotter or colder and will cause discomfort to the occupants of the building.

As explained in [38], the beginning of the occupied time (t_2) and the unoccupied time (t_5) are fixed at, in this case, 0700 h and

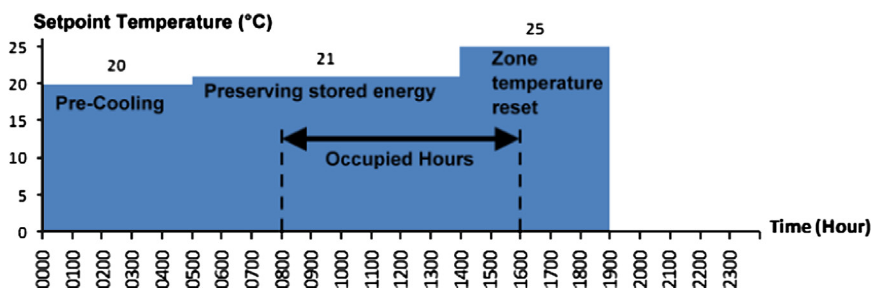

Fig. 8. Extended pre-cooling.

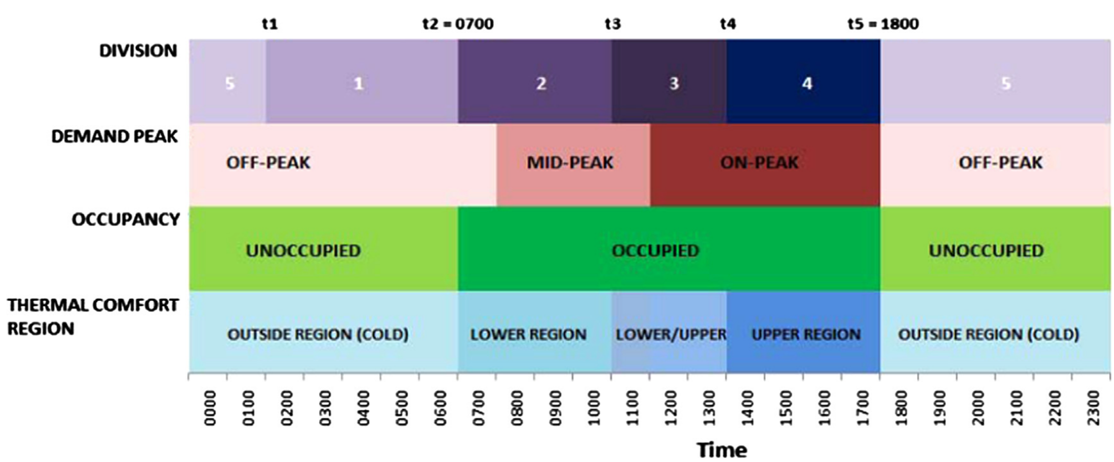

Fig. 9. The 5-period division.

Table 3
The 5-period division scheduling.

Beginning time	*Ending time*	*Occupancy status*	*Demand status*	*Scheduling status*
t_1	t_2	*Unoccupied*	Off-peak	Pre-cooling *with temperature as low as 18°C*
t_2	t_3	*Occupied*	Off/mid-Peak	*Maintaining the setpoint temperature in the lower half of the thermal comfort range (21–23°C) while saving the stored energy*
t_3	t_4	*Occupied*	Mid/on-peak	*Maintaining the temperature in thermal comfort range (21–25°C) with or without the contribution of stored energy*
t_4	t_5	*Occupied*	On-peak	*Maintaining the temperature in the upper half of thermal comfort range (23–25°C) with the contribution of the stored energy*
t_5	t_1	*Unoccupied*	Off-peak	*Turn OFF the HVAC system*

1800 h respectively. The other three time parameters t_1, t_3 and t_4 are simply set to be 0200 h, 1200 h and 1200 h respectively. The choices for these times are arbitrary and are not determined by the conditions of the weather outside the buildings [38]. In [38], t_3 was set to be t_4, which means that the HVAC will operate in four types of mode instead of five since t_3 and t_4 are combined and this is actually similar to scheduling technique in [29]. The result of the weekly energy savings made after using this technique has been compared with the step-up and linear-up scheduling strategies discussed in Sections 2.2.2 and 2.2.3 respectively and is summarized in Table 4. Table 4 shows that the 5-period division scheduling approach provides the highest energy consumption reduction as well as the highest cost saving ability compared to the step-up and linear-up scheduling techniques, while also considered the occupancy and energy demand status of the buildings.

t_3 and t_4 are set to be the same as it is assumed that more energy can be saved by setting the temperature to upper half of thermal comfort range as explained previously in [1,2] and [26]. In addition, possible values of t_1, t_3 and t_4, can simply be set to represent the 'best scenario' values. However, since t_1, t_3 and t_4 are set without concerning about the weather condition, the duration of the cooled air that can be stored and discharged is not optimized. These three parameters can be optimized by taking into account other factors including the weather effect in order to maximize the energy saving potential.

2.3.3. Aggressive duty cycling

Aggressive duty cycling of HVAC is a technique that turn on/off the system many times in a day just like the ASOO technique from [26]. However, in this technique, an occupancy sensor network has been established in the building to record the occupancy status of the rooms in the building. The recorded occupancy is used to schedule the start time and stop time for the HVAC system. Apart from using the occupancy sensors, occupancy level of a building could also be measured through Wi-Fi connection [39], wireless sensor network [40,41], radio frequency identification (RFID) [41] and camera observations [42]. The information can then be used in determining the optimum HVAC scheduling operation that is implemented with sensor interruption. The difference between this technique with ASOO is the on/off switching is done based to the current occupancy using the on-line sensor detection instead of pre-programmed on/off switching.

Table 4
Energy and cost savings potential of the advanced scheduling techniques.

HVAC scheduling strategy	*Energy consumption reduction (%)*	*Cost saving (%)*
Linear-*up*	*15.29*	*17.42*
Step-*up*	*21.49*	*24.35*
5-period division	*25.31*	*28.52*

In [43], before the occupied period, the HVAC is switched into the standby mode for several hours, during which the temperature is set to be low to save on the electricity cost, for the heating system case. The HVAC system in a particular zone is to be switched on exactly when occupants are detected (in case of early arrive) or exactly according to the normal building operation.

Meanwhile, between the start and stop time, the HVAC operation will be controlled directly by the occupancy sensors deployed in the building. When the space is classified as unoccupied, the HVAC will be turned off and when it is occupied, the HVAC will be turned on.

For the unoccupied period, since there is a possibly big time gap between the time the occupants start to leave the building until the building is completely unoccupied, normally all the HVAC is set to the standby mode exactly when the building is unoccupied. The HVAC system is also set to remain in the standby mode until later at night when it will be finally turned off. Early standby and late switch-off are used for normal HVAC operations of the building. Both time values are used in this work to see the effect of the aggressive duty cycling.

In the experiment done, during the building operating hours, the occupancies of zones were quite static, which means, it is occupied for a long period. Because of this, the effect of aggressive duty cycling cannot be seen clearly. In addition, the status of the HVAC of the zones during the experiment is not shown, which makes it hard to see the effect of occupancy change frequency on the power consumption. Since the power consumption of the HVAC also depends on its transient response, turning on and off will probably cause unsatisfactory transient response and overshoots, which will waste the energy [44–46] as well as wearing off the HVAC component more quickly [28]. Despite these shortcomings, this technique was able to save up to 11.59% electrical energy use of the building.

2.3.4. Optimized demand-limiting setpoint trajectories

This technique is implemented with the conventional HVAC scheduling during the discharge of the stored energy. Instead of simply increasing the temperature setpoint during cool energy discharge just like the step-up and -linear-up, this technique will determine or optimize the setpoint temperature trajectories during discharge operation to save up more energy and cost, as shown in Fig. 10. Three ways of optimizing the setpoint temperature for limiting the demand in buildings, called the 'demand limiting methods' have been proposed in [30], and are summarized in Table 5 below.

The SA and ESA methods put more focus on both the indoor and outdoor parameters in the optimization process. In [32], the performance for peak demand reduction by the three optimized techniques in Table 5 are compared with the conventional HVAC scheduling techniques (Section 2.2). The results are shown in

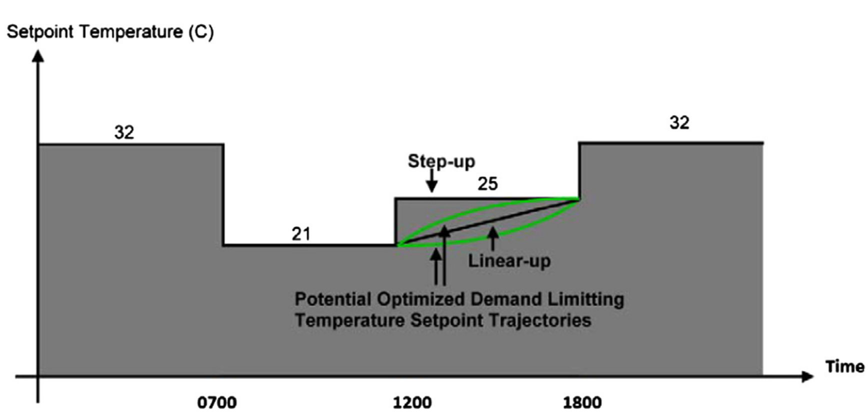

Fig. 10. Demand-limiting setpoint trajectories illustration.

Table 5
Demand-limiting setpoint trajectories optimization techniques.

Method	Description	Input/output parameters
Semi-analytical (SA)	Determines an analytical expression for the demand-limiting setpoint from a simple building model that characterizes the thermal interactions between the interior space and a shallow interior mass	**Output:** Zone air temperature **Inputs:** Outdoor temperature Thermal capacitance of shallow mass Thermal resistance between shallow and deep mass Thermal resistance between zone air and shallow mass Temperature of the deep mass Temperature of shallow mass Convective heat gain to the zone air Radiative heat transfer to shallow mass Zone sensible cooling load
Exponential setpoint equation-based semi-analytical (ESA)	Simple exponential equation for the demand-limiting setpoint assuming that all driving input conditions are constant during the demand-limiting period EAS produces an effective time constant for the equation that can be used to obtain the demand-limiting setpoint trajectory	**Output:** Zone air temperature **Inputs:** Temperature at the start of demand limiting Temperature at the start of demand limiting Time measured from the start of demand limiting period Duration of demand limiting period Zone air temperature upper Outdoor air temperature Thermal capacitance of shallow mass Thermal resistance between indoor and outdoor air Thermal resistance between zone air and effective building mass Thermal resistance between outdoor air and effective building mass Temperature of the deep mass Temperature of effective building mass Temperature of effective building mass Convective heat gain to the zone air Radiative heat transfer to interior building mass Solar radiation Zone sensible cooling load
Load weighted-averaging (LWA)	Setpoint trajectory for minimizing the peak load is estimated through a LWA of two control setpoint trajectories	**Output:** Average of two temperature trajectories **Inputs:** Two desired temperature trajectories

Table 6, which clearly shows that the three optimized techniques have higher energy saving potential compared to the conventional HVAC scheduling techniques. All the three optimized demand-limiting setpoint trajectories techniques have similar peak demand reduction performance. However, the optimized SA and ESA demand-limiting techniques are very complex as there are numerous amount of parameters that have to be taken into account, compared to the LWA technique that only requires two desired temperature trajectory inputs.

Table 6 shows that he SA, ESA and LWA optimization strategies give the highest peak demand reductions due to the optimized setpoint for a specific demand-limiting purpose. Nevertheless, in these strategies, only the setpoint temperature of the HVAC system is optimized. Time-variable parameters such as the start time and stop time of the HVAC system are not specifically optimized. Furthermore, the effect of outside weather on the indoor temperature was not considered, which may cause discomfort to the occupants in the building [38,47–51]. In [25], it has also been shown that the stop time and start time of the HVAC operation can be affected by the outdoor temperature. One possible way to compensate for this is by reducing the HVAC's setpoint temperature or extending the duration of the pre-cooling process. Since by switching off the HVAC system exactly when the space is unoccupied can cause the stored energy inside the building space at the end of HVAC operation to be wasted, the implementation of 'early switch off' strategy can be considered so that the existing stored energy can be used to provide comfort even after the HVAC is switched off in order to reduce the electricity usage. The demand-limiting strategies also do not consider the pre-cooling temperature, which may results in even better energy saving potential if optimized.

Table 6
Performance evaluation of the optimized demand-limiting setpoint trajectories techniques.

HVAC scheduling method	*Peak demand reduction*
Baseline (reference)	–
Linear-up	*19%*
Step-up	*38%*
SA	*40%*
ESA	*42%*
LWA	*41%*

3. Predicted Mean Vote (PMV)

Human body comfort is measured not only from the air temperature value, as in the scheduling techniques discussed in Section 2. Instead, in the PMV, which according to [52,53] and [54] is the most widely applied comfort index, several parameters are taken into consideration in calculating the index value, which varies from '−3' (very cold) to '+3' (very hot) with '0' being the neutral index value. There are six environmental condition parameter values inside a particular space that are used in PMV calculation. They are the human

activity (metabolic rate), types of clothing, air temperature, mean radian temperature, air velocity and the indoor relative humidity.

However, according to [52], the indoor climatic conditions are related to or affected by the outdoor climatic condition. As an example, the weather or outdoor temperature will affect the indoor air temperature and the mean radiant temperature [55]. This indicates that the outdoor temperature can be indirectly used in the PMV calculation. In predicting the PMV indices for days ahead, outdoor temperatures can be obtained from weather forecast data, which usually provides the one-week outdoor temperature prediction. By having the future outdoor temperatures, future indoor air temperatures and mean radian temperatures also can be obtained.

Instead of just assuming the suitable temperature set points throughout the day, as done in most of the scheduling techniques, more accurate comfortable temperatures can be obtained using the PMV index. With the outdoor and indoor temperature relationship, HVAC system can be programmed to be adaptable to the weather condition so that it can consistently provide comfort, no matter how the weather changes. By using a fixed temperature setpoint throughout the day, occupants will experience discomfort when the outdoor temperature changes drastically. Therefore, it is important to use a specific comfort index, for example, the PMV, in ensuring an optimized operation of the HVAC system.

4. Conclusions

HVAC scheduling techniques can be divided into three classes—basic scheduling, conventional scheduling and advanced scheduling. Basic scheduling operates the HVAC system by simply manipulating the ON and OFF states for the whole operating hours with a fixed setpoint temperature being used. Meanwhile, the conventional scheduling uses pre-cooling or pre-heating techniques to reduce the peak demand with the use of several setpoint temperatures throughout the 24-hour operation. The advance scheduling is the improved version of the basic and the conventional scheduling techniques with which the energy saving potential is proven to be higher than the conventional scheduling. Among these techniques, the demand reducing technique, which requires pre-cooling or pre-heating, is the most used method in HVAC scheduling. This technique is used widely in order to take the advantage of low electric price during off-peak hours. This technique has been improved by optimizing some related parameters where the energy saving potential can be further increased.

However, some problems regarding the advanced demand-reducing technique, particularly the optimized demand-limiting setpoint trajectories, have been identified. The problems include the electrical energy wasted due to the 24-h non-stop operation regardless of whether the space is occupied or not, the energy usage of the pre-cooling/heating process, the limited number of parameters being optimized and the exclusion of a human comfort index in its implementation.

An improved demand reducing scheduling technique needs to be developed in order to obtain a higher energy saving HVAC operation. The new technique must utilize all the 5 time divisions including the OFF state duration to avoid energy wastage during off-peak. Early switch off also can be implemented to utilize all the stored cooled air/heat energy from the pre-cooling/pre-heating. The pre-cooling/pre-heating in the new technique must be implemented for several hours during the off-peak period before the beginning of the peak hours, replacing the night setback to take the advantage of the low electricity prices. The duration and setpoint temperature for some of the 5-time sections including the pre-cooling/pre-heating, and zone temperature reset needs to be optimized in order to compensate for the weather conditions so that occupants in the space will not experience any discomfort. This may include pre-determining the setpoint temperatures based on, for example, the weather forecast information. Finally, to ensure a comfortable operation, the new technique needs to take into account some comfort indices such as the PMV.

Acknowledgment

This project is supported by the Ministry of Higher Education and Universiti Teknologi Malaysia under the Research University Grant 00G19.

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